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RESEARCH ARTICLE

Potential strategies offered by animals to implement in buildings' energy performance: Theory and practice

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Abstract
The strategies for thermal regulation and environmental control found in nature are countless. In this article, a parallelism between animals and building energy systems is defined in order to identify and emphasize the immediate opportunities that biomimicry offers for future research. The motivation was the need to find alternative solutions to tackle problems mainly in the efficiency of heating, ventilation and cooling systems. Due to the wide range of possibilities offered by animals, this study is largely limited to the strategies that cold-blooded animals have developed through evolutionary adaptation to the environment.
The method used for the analysis is based on a solution-based approach. Firstly, different animal thermoregulation strategies are defined (biological domain). Then the strategy is analyzed and classified into three categories. This classification is essential in order to formulate the parallelism with building systems (transfer phase). The final step is to identify the potential implementation (technological domain).
This approach has been seen to be useful in creating new research opportunities based on biomimicry. In addition, suitable solutions arising from multidisciplinary team research

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are presented as promising answers to the challenges that building energy systems face nowadays.

1. Introduction

This study arises from the technological enhancement necessities detected in building energy systems from the professional and teaching experience in this area of the research team since 2001 (Martín Gómez, 2011; Martín-Gómez and Zuazua-Ros, 2012; Martín-Gómez, 2005). These systems are those responsible for energy consumption in buildings, and may be any equipment, machinery, or process or a combination of these (Harish and Kumar, 2016), including other passive elements such as building construction systems or the design itself that directly affect the energy requirements. The framework of necessities detected in this study is limited to the building design, construction systems and Heating Ventilation and Air Conditioning (HVAC) systems, which, in the end, are responsible for most energy use. The potential improvements in this field are made by applying the science of biomimicry, using references from nature, as well as other theoretical studies existing in this field (Reddi et al., 2012; Pacheco Torgal et al., 2015; Santamouris, 2016; Samuel et al., 2013; Gul and Patidar, 2015; Chua et al., 2013). Figure 1 summarizes the workflows in this study.

A living being or organism is a complex material assemblage. It makes use of communication systems, which create a relationship between the living being and the environment. So, a systematized exchange of energy and matter is created in the organism in order to maintain the basic life functions: nutrition, relationship and reproduction (Nealson and Conrad, 1999).

The science that uses this knowledge for any kind of human purposes is called biomimicry. J. Benyus defines biomimicry as "learning from and then emulating natural forms, processes, and ecosystems to create more sustainable designs". This branch of knowledge has had a clear relationship with building design (John et al., 2005), mainly in factors such as the shape (Pawlyn, 2011), where the golden ratio is one of the most well-known concepts. Other factors involving buildings and nature can be classified into three groups. (**1**) **Envelope** as building 'skin' concept (Reddi et al., 2012). The existing studies include advances in façades and roofs, such as new bionic designs or the use of organic materials (Šuklje et al., 2013; Badarnah and Knaack, 2007a, 2007b). (**2**) **Structure**, considering the design of high-rise buildings as trees (Yiatros et al., 2007). (**3**) Environmental control as **indoor thermal comfort and air quality**. Animals seek an appropriate habitat for living, as humans do in buildings. The research that gathers such concepts is mainly focused on passive ventilation strategies (Worall, 2011; Turner and Soar, 2008).

In this case, the analysis is focused on how the energy required in buildings can be optimized and reduced in order to achieve a certain indoor thermal comfort and air quality, based on animal strategies. Thus, the objectives of this study are:

- to define a parallelism between animal and building energy systems and to present the methodology used
- to analyze the results obtained in the project and identify the immediate research opportunity areas that animals can offer.

This type of research offers solutions midway between brainstorming and a basic technology readiness level. However, it has been demonstrated that searching for generic problems, solutions, or evaluation criteria should help in finding specific problems, solutions, or evaluation criteria (Sarkar and Chakrabarti, 2014). Besides, once the idea is generated, it is a matter of time and dedication for a potential solution to be validated scientifically. However, a recent study also concluded that systematic and organized methods for bioinspired design should be sought to effectively make the most of our knowledge of the designs found in nature (Glier et al., 2014).

In a first stage, the paper describes the research framework and general parallelisms found between buildings and animals. Then the methodology is presented, the research opportunity areas are defined using three levels: the biological domain, transfer phase and technological domain.

2. Basis of the research framework

The study framework of this article is part of the project called 'Redesign of building energy integration from animal metabolisms' (Martín-Gómez et al., 2015) which brings biologists and architects with both design and technological profiles together onto the same work team. The project seeks to explore new design strategies of energy systems and building services from a critical analysis of cold-blooded animals'. However, the research began with a wide perspective and was then restricted to the area of energy systems and the necessities detected in urban and building energy systems. The motivation was the need to find solutions to tackle problems mainly in the efficiency of heating, ventilation and cooling systems. And these alternative solutions will be born of the approach of disciplines such as architecture, building and mechanical engineering, control systems, chemists and biologists, as the previous works of the authors have shown.

2.1. Animals and buildings

Generally, in the relationship between architecture – (biomimicry) – biology, a major challenge is to provide a systematic selective design methodology capable of identifying the most relevant systems. Subsequently, it is necessary to abstract the strategies and mechanisms to be implemented in buildings (Badarnah and Kadri, 2014). This process is outlined in Figure 2.

Two illustrative cases are be the application of Allen's and Bergmann's rules. These are two examples of how living beings have adapted to the environment through evolution, which is the main rule for sustainable design in buildings:

- Allen's rule broadly states that the body shapes and proportions of animals (endotherms) vary with the climatic temperature, minimizing the surface to reduce heat loss in cold climates or maximizing the exposed surface area to increase heat loss in warm climates. Although it was originally thought to only relate to endotherms, it is also valid for ectotherms (Alho et al., 2011). There has also been renewed interest in Allen's rule due to global warming and the "microevolutionary changes" that are predicted by this rule.
- Bergmann's ecogeographic rule states that the largest specimens of a species are found in colder environments, while smaller ones are found in warmer climates (Bergmann, 1848). Based on this rule, facts like gigantothermy (Paladino et al., 1990) and the relationship between vernacular architecture and the climate can be validated.

2.2. Ectotherms and building energy systems

Various parallelisms between animals and buildings have been studied (Pacheco Torgal et al., 2015; Goel et al., 2014; Vincent, 2009, 2014). However, this study is limited to the improvement of building energy systems, particularly those to do with HVAC systems, using solutions similar to those of living things. The lack of a biological data-base from an engineering point of view regarding building physics and services is surprising (Bar-Cohen, 2006). Only a very few studies about building services with a biological inspiration have been found: mechanical design (e.g. pumps inspired by birds (Thiria and Zhang, 2015)), solar energy using by photosynthesis concepts (Gust et al., 2001; Plotkin et al., 2010) and nanoscale devices (Gust et al., 2001) or enhanced photovoltaic panels inspired by *fovea centralis* (Shalev et al., 2015).

The most remarkable processes identified in some animal species point to thermal regulation, environmental gas control and respiratory, neural or blood networks. For living organisms, achieving thermoregulation objectives is a matter of survival, as they have developed strategies that have been enhanced over millions of years. To complete this hypothesis, it can be stated that living beings and buildings share two major objectives in their adaptive evolution to the environment:

(1) Thermal regulation in animals is equivalent to the temperature control in buildings (Martín-Gómez, 2006).
(2) The Indoor Air Quality requirements demanded in buildings resemble the environmental control of living things. This is particularly interesting in the case of social insects (Bermejo-Busto et al., 2016).

Rather than studying all living beings, this study focuses on cold-blooded animals. The main reason comes from the similarity of cold-blooded animals to nZEB buildings. The

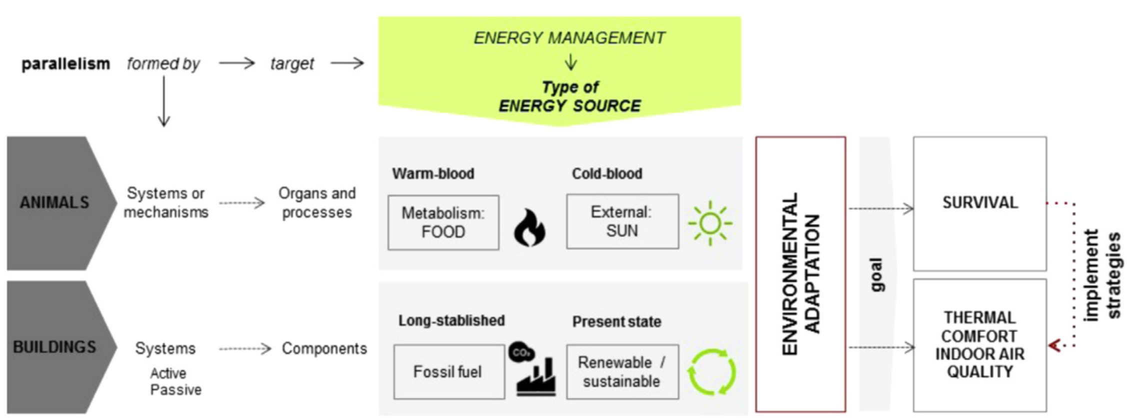

Figure 1 Concept schema showing the main goal of the study as regards workflows followed.

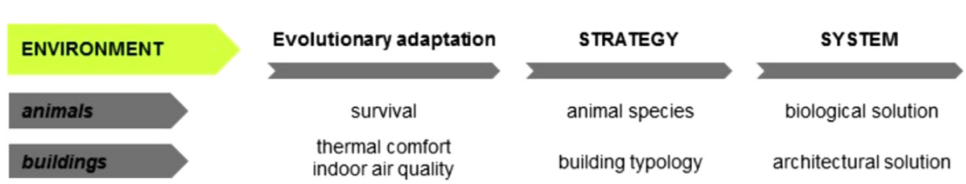

Figure 2 This figure shows the sequence of concepts from the widest origin (environment) to the final solution framework (system). Buildings need to adapt to the environment as well as animals have done over history. In the case of animals, the final aim was to survive in certain conditions while buildings seek to offer a certain comfort and air quality with minimum energy consumption. The strategies developed for this purpose differ between the animal species and between building typologies.

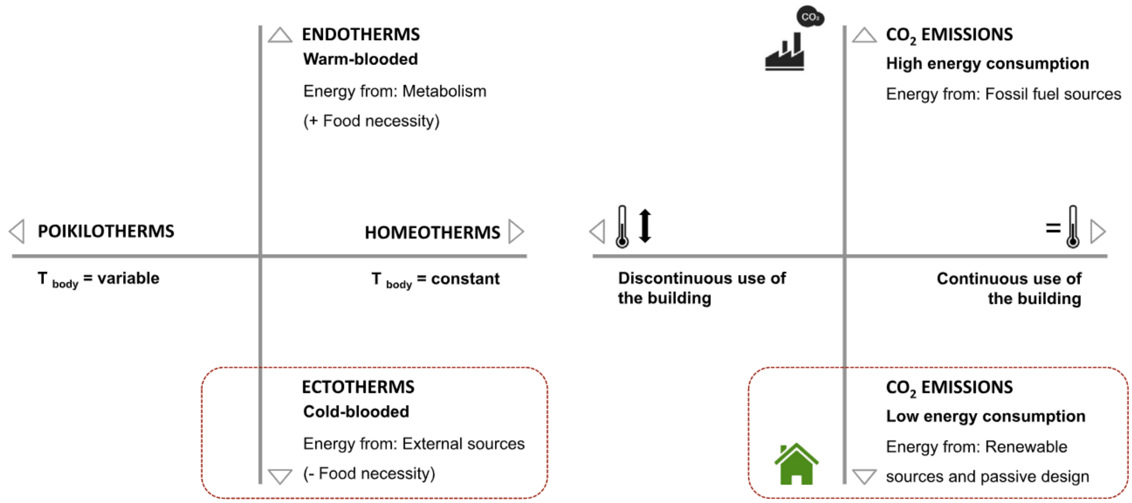

Figure 3 Simplified comparison of ectotherm animals and low energy consumption buildings. Putting the reality of biology simply, ectotherms are animals that require less food to meet their biological needs and make better use of external energy sources. This parallelism has been moved to buildings to provide a broader range of temperatures, ensuring indoor comfort conditions and implementing solutions to reduce CO_2 emissions.

graphical summary is given in Figure 3 and responds to the following consideration:

- Regarding heat gain and production, animals are classified as endotherms (which regulate their body temperature by means of their metabolic activity) and ectotherms (which regulate their body temperature by means of external sources). This is comparable to the classification of buildings depending on CO_2 gas emissions, where the 'polluters' would be at one end and nZEB at the opposite (see Figure 3).
- Regarding their internal temperature variations compared to the environmental temperature, homeotherms have a constant body temperature, regardless of the external environment. However, the body temperature of poikilotherms varies depending on the environment. Similarly, buildings can be classified into two groups: those that have discontinuous use (are turned 'on' and 'off') and buildings such as hospitals that require constant temperatures 24 h a day, 365 days a year.

This image (Figure 3) presents a simplification of reality and has been the intellectual trigger and the basis for reflection on the results obtained.

Even though the concept of warm/cold-blood is considered lax in terms of scientific biology, this figure has consistently been the focus of researchers and is a useful concept when creating a theoretical relationship between building and biology. Regarding building energy systems, other general parallelisms are proposed:

- There are net equivalences between components in biological systems and in building services: the heart as a fluid pump, air-handling units as buildings' lungs, pipes as blood vessels, data network equivalent to the neural network, and so on.
- Similar measurement parameters are used. Thus, the concepts of indoor/body and outdoor/ambient temperature are perfectly associated. The biological concept of size and surface-to-volume ratio can match the form factor of a building. Moreover, the metabolic rate (W/kg) may be considered a unit equivalent to the energy ratio consumption (kWh/m^2) of a building (Zuazua-Ros et al., 2016a).

From this context, what are the current challenges in building energy systems? The problems with this type of installations may refer to the design (Fumadó Alsina, 1996), their implementation (Martín-Gómez, 2006), maintenance (Fumadó and Paricio, 1999) or the use made by their occupants (Wener and Carmalt, 2006). All this forms a boundless spectrum, so the orientation in the exploration of solutions is mainly based on the earlier work of the research team in this field. The prioritized goals are summarized in the following main groups:

- Energy load and consumption: This includes the heat management drawbacks that may appear in buildings, caused by the design itself, incorrect system implementation, a lack of prevision regarding the end use of the building… All this usually implies a higher energy demand, unexpected cooling loads, thermal discomfort or poor air quality. The integration of active systems in the building design is also included here.
- System optimization: this category includes several concepts such as systems control, which may be referred to as Building Energy Management Systems (BEMS), development of autonomous systems, network design optimization (ducts, piping, calculations…) and equipment requirements such as maintenance costs, water consumption, noise or vibrations.
- New materials: This group refers to all the possibilities that arise from the development of new materials or components for building systems. Some examples are low carbon footprint materials, development of organic solutions or the design of a novel component to optimize the performance.

Though the following methodology strategies from animals under thermal regulation requirements are analyzed and a relationship with existing challenges in building energy systems is made.

3. Methodology

There are two main approaches to implementing biomimetics, as the scientific literature has shown and Badarnah has stated (Badarnah, 2012): problem-based and the solution-based approaches. The investigation begins with the work of a team of biologists seeking cold-blooded animals which have developed interesting strategies that allow them to regulate their temperature or to achieve optimal environmental conditions. Therefore, the method used is a solution-based approach. Its aim is to find descriptions of biological phenomena which are used to develop solutions for a simple problem (Mak and Shu, 2008). The structure followed in order to manage this interdisciplinary knowledge is summarized in Figure 4.

Biological domain:

- It begins with the initial selection of 200 research publications corresponding to 40 animals or general biological strategies, from which approximately 20 cold-blooded animals are chosen.
- The biological results are identified.
- The main concepts are extracted. They are classified into six groups, following our own criteria, which will later be explained.

Transfer phase:

- The environmental conditions, evolutionary strategy and response mechanisms are analyzed.
- The equivalent function in buildings is identified and the context defined from environmental requirements.
- Brainstorming to find bio-inspired ideas, using the definition of the problem resulting from the biological solution.

Technological domain:

Transposition of the biological solution is carried out either by parallelism with the starting conditions or optimizing solutions in the field of building services.

Simulation of design principles with the development of new ideas. In fact, three of these are being developed by researchers. However, the aim of this paper is limited to the numerous hypotheses that appeared during the process.

The abundance of information handled demanded a specific management data collection and classification system consistent with the objectives of the project, thus:

(1) A database was created using FileMaker Pro 13v5 software. Each record gathers the biological information of the animal and its potential applications in building systems, as well as all the bibliographical information (Figure 5).
(2) Although there were other categorizations similar to the one proposed in this work (Badarnah, 2012), we decided to develop our **own classification**, due to the specific complexity of building services which did not easily fit into the previous studies analyzed. The strategies tested were classified into six groups, depending on the system involved. This classification is an open scheme that seeks to emphasize the concepts related to energy use in buildings.

Academically, the proposal posed a reassessment of the paradigm established in the methodology of the understanding of energy systems in buildings, with an alternative view from another area of knowledge. Authors propose a disruptive methodology, based on 4 years of experience with proven results, which allows the extrapolation of solutions, models and systems from biology to the technical world conceptually, beyond the copying or adaptation of existing forms.

4. Method application and results

Regarding the experience of research with biomimicry, the following points have been especially relevant for the research group:

- The biologist group had a great knowledge of their area without awareness of the possibilities that could be valuable for buildings. This is the reason for the necessity to foster such collaboration among architects, engineers, biologists and experts from other fields of knowledge.
- Following the previous point, it is remarkable that the study of almost every animal analyzed offered either new implementation options for existing building energy systems, or interesting hypotheses for the design of new solutions.
- It has been demonstrated that by considering one and the same animal strategy, different suitable solutions for buildings, or for the systems that integrate them, have been generated.

The schema explained in the methodology (Figure 4) is used to show the results, divided into three levels: the biological domain, transfer phase and technological domain.

4.1. Biological domain

The studied animals make use of several processes to guarantee their thermal regulation and/or maintain an optimal environmental control. These natural models are summarized in Table 1.

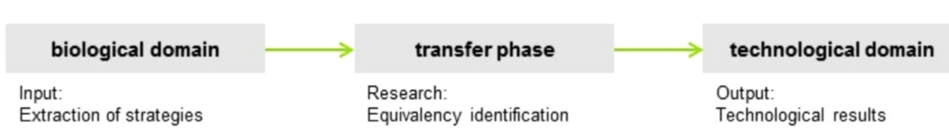

Figure 4 Solution-based approach. Steps defined by Badarnah (Badarnah, 2012), based on Biomimicry 3.8 (Group, 2014) (Baumeister et al., 2014) and Goel (Helms et al., 2009).

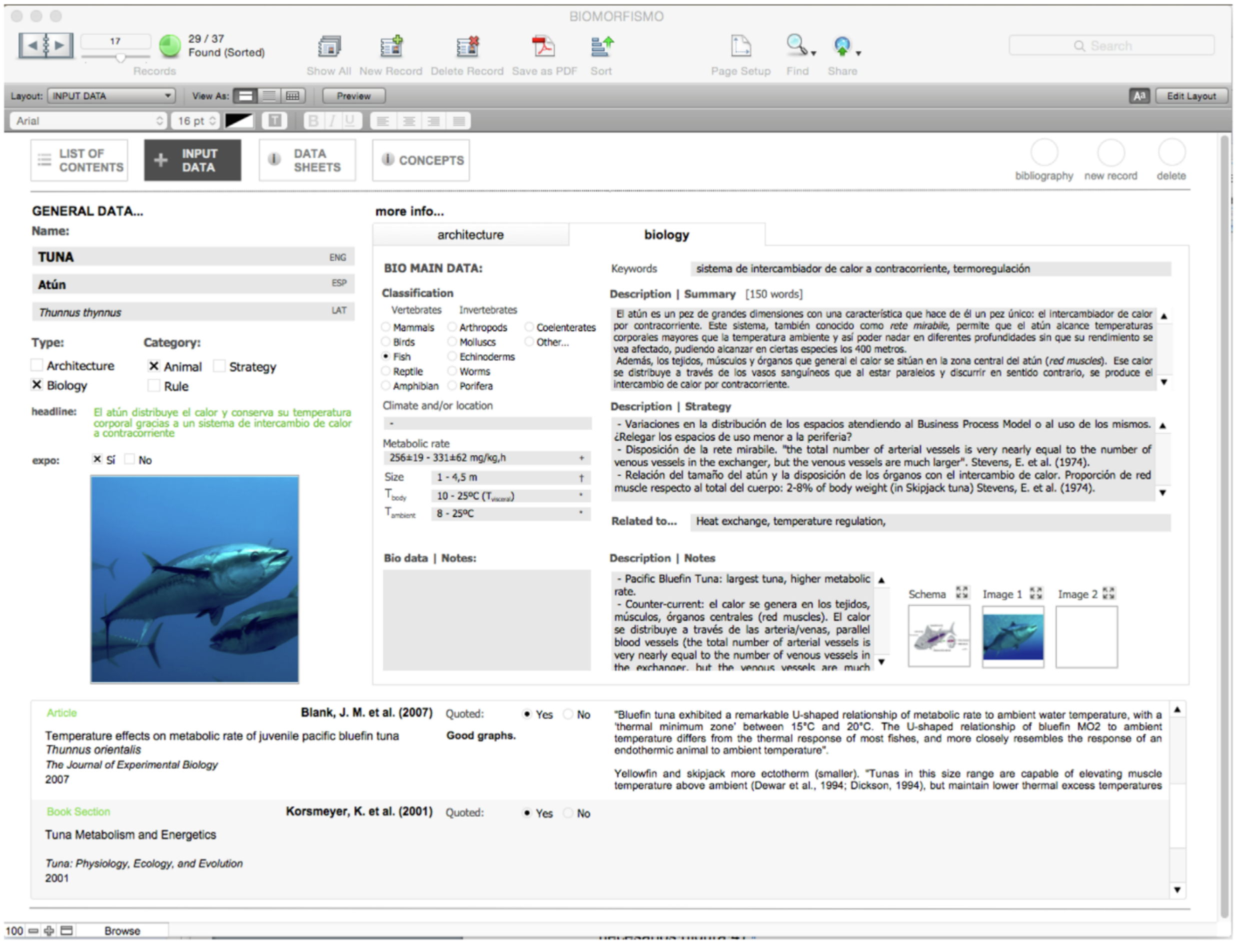

Figure 5 Animal database image. Each sheet refers to one animal including general biological information, a brief summary and strategy description. Some pictures and schemes may be added as well as personal notes. At the bottom, the most useful referees are also included.

The strategies examined are classified into three major categories: those corresponding to a system, a process or an action. Some actions and strategies have more than one objective, in the same way as there are animals with more than one strategy to achieve their aims. Firstly, the main concepts are arranged into six groups. In a second stage, the strategies are divided into processes according to their objective and finally, the last classification relies on how they work to achieve them (Figure 6). This classification is an open scheme for future research or additions:

(1) Heat control. This group includes the strategies generated by metabolic activity. They are compared with the heat and cold generation and their corresponding energy consumption in building services. The processes detected in this subject are, on the one hand, internal body-heat use, involving actions such as grouping bodies to avoid heat loss or the use of heat in a heat-exchange system. On the other hand, there is metabolic rate variation, where the functioning rate is altered in order to save energy. This variation may be focused on the heartbeat pattern or on the respiratory pattern.

(2) Organic material use. Some animals use materials such as thatch or mud to maintain their temperatures by increasing body insulation. Other strategies are the creation of a cocoon around the animal to minimize water evaporation or to produce an appropriate environment for a specific process, e.g. the metamorphoses of the silkworm. In the cases analyzed, the cocoon material is always self-created by the animal. In HVAC systems, these actions inspire the possibility of using new organic materials or components.

(3) Air or respiratory control. Animals seek to control the movement of air, sometimes by forcing the flow or obstructing ducts to reduce ventilation. This is directly related with building compartmentalization for air-control purposes, not usually considered essential. The variation of the surface-to-volume ratio is also a useful technique to control the movement of air, usually related to tent or nest building in social insects.

(4) Solar control. The sun is the main energy source for ectotherms. The use of this renewable source in buildings is a field in continued development. Solar control includes either obtaining heat or rejecting it. This basic control process underlines the importance of the orientation on both an individual (e.g. basking or flapping) and a social scale (nest building). Some animals show more complex skills. The reflectance and color-change ability for thermal control are studied. This reflectance may be achieved with nanoscale structure (as in the case of morpho butterflies) or

Table 1 Animals' main strategy description.

Animal English / *Latin*	**Biological model summary**	**Reference**
Alligator *Alligator mississippiensis*	Metabolism that allows heating up faster than cooling down.	(Seebacher and Franklin, 2007; Smith et al., 1978; Turner and Tracy, 1985)
Ants[a] *Acromyrmex heyeri*	Thatched nest construction with ventilation holes to protect larvae and fungus that are placed inside.	(Bollazzi and Roces, 2010a), (Bollazzi and Roces, 2010b)
Caterpillars[a] *Eriogaster lanestris*	Indoor temperature maintained within a limited range in comparison with a wide range of ambient temperatures.	(Ruf and Fiedler, 2002), (Kevan et al., 1982)
Chamaleon grasshopper *Kosciuscola tristis*	Color change independent of metabolism.	(Umbers, 2011; Umbers et al., 2013)
Desert grasshopper *Calliptamus barbarus*	Evaporative cooling to maintain body temperature in lethal temperatures.	(Prange, 1990; Roxburgh et al., 1996)
Desert iguana *Disposaurus dorsalis*	Preservation of vital functions within a range of $\pm 5\,^{\circ}C$ while ambient temperature has a variation of $40\,^{\circ}C$. If body temperature is lower than $28\,^{\circ}C$, digestive functions are stopped.	(DeWitt, 1967; Norris, 1953)
Desert snail *Sphincterochila boissieri*	Cooling the inside of the shell to avoid exterior lethal temperatures.	(Taylor et al., 1971; Ward and Slotow, 1992)
Eastern fence lizard *Sceloporus undulatus*	Difference between the optimal temperatures of the locomotor system (wide range) and the digestive system (tighter range).	(Angilletta et al., 2002; Langkilde and Boronow, 2012)
Fiddler crab *Uca panacea*	Use of combined strategies for temperature control: dissipation surface, color change and evaporative cooling.	(Darnell and Munguia, 2011; Wilkens and Fingerman, 1965)
Honeybee[a] *Apis mellifera*	Indoor temperature control in the beehive through social organization.	(Bonoan et al., 2014), (Sudarsan et al., 2012)
Knife-footed frog *Cyclorana cultripes*	Creation of a protective layer around itself to diminish the water loss in dry seasons.	(Tracy et al., 2008, 2007; Withers and Thompson, 2000)
Marine iguana *Amblyrhynchus cristatus*	When diving in cold water, blood is not transferred through the lungs to avoid heat losses, optimizing the oxygen requirements of the blood.	(Baker and Fred, 1970; White, 1973)
Morpho butterfly *Morpho didius*	Use of the effect of solar light diffraction to control body temperature.	(Kertész et al., 2013), (Barton et al., 2014)
Reed frog *Hyperolius viridiflavus*	Waste storage in the epidermis in order to minimize heating and water loss.	(Kobelt and Linsenmair, 1992; Schmuck and Linsenmair, 1997)
Sea star *Pisaster ochraceus*	Heat dissipation through the appendix, even making use of autotomy to survive to high temperatures.	(Pincebourde et al., 2013, 2009)
Silkworn *Bombyx mori*	Creation of a cocoon during the metamorphosis phase, which can control the quality and temperature of indoor air.	(Roy et al., 2012; Tulachan et al., 2014)
Termites[a] *Macrotermes michaelseni*	Construction of nests, structures characterized by having ventilation systems with the aim of controlling the indoor air quality.	(Fuller and Postava-Davignon, 2014; Turner, 2001, 1994)
Toco-toucan *Ramphastos toco*	Use of the bill as a heat dissipation element to regulate its body temperature by the expansion of blood vessels.	(Tattersall et al., 2009)
Tuna *Thunnus thynnus*	Distribution of interior heat and conservation of body temperature thanks to a counter-current exchange heat system.	(Blank et al., 2007; (Korsmeyer and Dewar, 2001)

[a]Social insects.

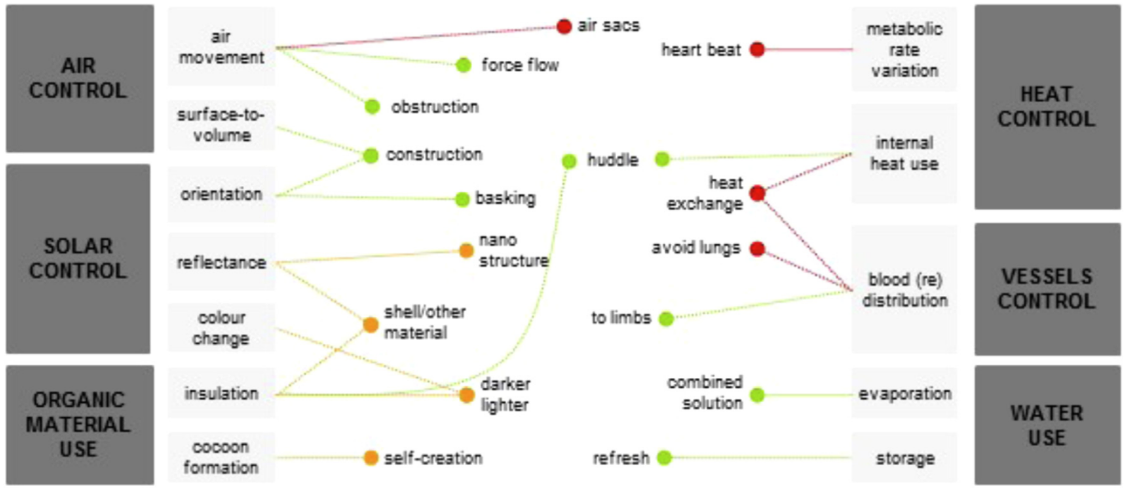

Figure 6 Solutions are grouped into Level 1 (six proceedings and systems), Level 2 (12 processes) and Level 3 (16 actions). The green dot corresponds to solutions mainly related to energy load and consumption, the red dots to system optimization and the orange dots to new materials or components.

on a larger scale (the desert snail's shell). The relationship between skin-color change and thermal regulation is studied in some animals (e.g. lizards and chameleon grasshoppers), although how it works has not been found with certainty. Usually the animals change to a darker or lighter color to increase or decrease heat gains.

(5) Vessel control. The actions in this group are related to blood circulation, and therefore, with plumbing systems in buildings. Two means of vessel control are established. On the one hand, the ability to adapt the surface-to-volume ratio of blood vessels through dilatation or constriction of ducts. On the other hand, the blood redistribution process that some animals use, e.g. when marine iguanas avoid blood circulation around the lungs in cold temperatures or when a sea star uses its limbs as heat sinks.

(6) Water use. The relationship of this group with thermal regulation is determined basically by means of water evaporation strategies or the use of water to refresh spaces.

4.2. Transfer phase

Within this phase we analyze environmental factors, the evolutionary strategy and the animal response mechanisms. The aim is to identify similar functions in building or engineering and define a context from environmental requirements.

The most complex part of the project, the basis for success or failure, is included in this phase. The researchers held several brainstorming sessions to find bio-inspired ideas, using the definition of the problem which is at the source of the biological solution. Obviously, these working sessions were driven by the professional experience of the researchers as well as by the intellectual exercise so as to suggest specific parallelisms between the animals studied and buildings.

These solutions are classified into the six procedures and systems mentioned above, establishing the following similarities with HVAC services: metabolism and the building heat use, including storage and dissipation; biological organic material use and creation of new thermal materials and components; respiration control comparable with ducts, air handling units or other air and ventilation systems in HVAC; the solar control found in animals could considerably improve the existing solar strategies in buildings; their vessel control could also produce developments in plumbing systems/networks; finally, water usage mainly refers to evaporative cooling strategies.

The process described and the approaches used are summarized in Table 2.

4.3. Technological domain

Based on the models analyzed, several technological hypotheses were proposed and classified into three groups depending on scale:

(1) **Building**: This is the architectural scale and comprehends the parameters that may affect the building design. They are usually challenges or improvements that must be made in the early stages of the project.
(2) **Systems**: Building services design, distribution networks or constructive design of active envelopes.
(3) **Components**: New devices or construction elements.

Although it is out of the scope of this research project, a higher scale could be considered for implementation in a group of buildings, that is, in the urban environment. The targets that arise from the proposed hypotheses which may respond to current challenges in the industry could be grouped as follows:

(1) Energy load and consumption:

- Heat storage: One of the first approaches is to make a redistribution of generated heat with unexplored solutions, for instance, relating to the business process carried out in the built space.

Table 2 Transfer phase resume.

Biological domain				Goals					Technological domain	
Animal	Strategy			Load and energy management			System optimization	New materials	Objectives	Application scale
	System	Process	Action	Heat gain prevention	Heat storage	Heat dissipation				
Alligator	Heat control	Metabolic rate variation	Heart beat		•		• •		Speed enhancement in pumping systems in plumbing installations.	System
Ants*	Air control	Air movement	Force flow	•		• •	•		Ventilation openings optimization. Passive ventilation control.	Building
Caterpillars*	Air control	Surface to volume	Construction	• •					Implementation of geometrical decisions.	Building
Chameleon grasshopper	Solar control	Color change	Darker/ Lighter					•	Design of a color protocol.	Building
Desert grasshopper	Water usage	Evaporation	Combined solutions	• •		•	•		Analysis of the increase of natural ventilation flows when temperature is high.	System
Desert iguana	Heat control	Metabolic rate variation	Heart beat				• •		In multi-use buildings, improvement of the available energy management.	System
	Solar control	Color change	Darker/ lighter	•				• •	Material or facade that changes its color depending on the temperature.	Component
Desert snail	Air control	Air movement	Force flows	•		• •	•		Implementation of indoor air micro-currents for temperature control.	Building
	Solar control	Reflectance	Shell					• •	Materials for humidity control between spaces.	Component
Eastern fence lizard	Metabolism	Metabolic rate variation	Heart beat				• •		Optimization of the processes of energy distribution.	System
Fiddler crab	Water usage	Evaporation	Combined solutions			• •			Evaporative cooling facade design. Multiple-solution integrations within a system.	System
Honeybee*	Air control	Air movement	Obstruction	• •	•	•			Division of elements in atrium spaces to diminish losses caused by air currents. Can be also applied to double façade systems' air cavity.	Building

Table 2 (*continued*)

Biological domain				Goals					Technological domain	
Animal	Strategy			Load and energy management			System optimization	New materials	Objectives	Application scale
	System	Process	Action	Heat gain prevention	Heat storage	Heat dissipation				
	Water use	Storage	Refresh						Use of stored water to refresh spaces	Building
Knife-footed frog	Organic material use	Cocoon formation	Self-creation			●		● ●	Creation of a material based on proteins able to minimize water evaporation.	Component
Marine Iguana	Heat control	Internal heat use	Huddle	●	● ●	●			Reorganization of spaces to decrease heat losses.	Building
	Vessels control	Blood redistribution	Avoid lungs				● ●		Drive heat to spaces without being treated in an AHU.	System
Morpho Butterfly	Solar control	Reflectance	Material	●		●		● ●	Design of a facade that diffracts light.	Component
	Solar control	Reflectance	Nano-structures					● ●	Gas detection sensors based on light reflection.	Component
Reed frog	Organic material use	Cocoon formation	Self-creation					● ●	Design and application of sewage-water based material that diminishes overheating.	Component
Sea star	Vessels control	Blood redistribution	To limbs	●		● ●			Heat dissipation making use of peripheral volumes in buildings.	Building
Silkworm	Organic material use	Cocoon formation	Self-creation					● ●	Material for air filters.	Component
	Organic material use	Cocoon formation	Self-creation				●	● ●	Material for thermoelectric systems.	Component
Termites*	Air control	Air movement	Force flow			● ●	●		Passive ventilation optimization for temperature control.	Building
Toco-toucan	Vessels control	Blood redistribution	To limbs			● ●	●		Integration of radiant surfaces to dissipate heat.	System
Tuna	Heat control	Internal heat use	Huddle	● ●	●	●	●		Spaces division or layout for heating demand optimization.	Building
	Heat control	Internal heat use	Heat exchange	●			● ●		Heat recovery in cascade connection.	System

● ● Main improvement.
● Secondary improvement.
*Social insects.

Table 3 Strategies and hypothesis that have been developed by the research team.

Animal	Proposed solution	Scale	Method	Results	Ref.
Honeybee	Thermoelectric façade optimization based on airflow control in beehives.	System	Theoretical analysis	Two optimization strategies (1) façade ventilation system improvement for a better dissipation/storage (2) control-system design based on honeybees' behavior.	(Bermejo-Busto et al., 2016)
Tuna (I)	Office building work-space layout design for an optimal heating demand based on the tuna's muscle configuration.	Building	Building simulation	Simulations carried out in different city and space configurations in which up to 8% of heating demand can be reduce attending the work-space design layout.	(Zuazua-Ros et al., 2016a)
Tuna (II)	Heat recovery ventilators in cascade configuration based on tuna's body temperature control.	System	CFD simulation	Having simulated the new configuration in different climates, up to 44.5% of energy could be saved, making it a promising solution for heat recovery in buildings.	(Bermejo-Busto et al., 2017)
Toco toucan	Heat dissipation panels to reduce the drawbacks from cooling towers	System/ Component	Prototype	After analyzing the prototype under different conditions, between 100 and 400 W/m^2 heat can be dissipated through these external cooling panels.	(Zuazua-Ros et al., 2016b; Zuazua-Ros et al., 2017a)

- Heat dissipation strategies are also proposed which would use the geometric design of buildings, with ventilation systems that retain heat or dissipate it in atrium spaces. Alternative solutions could be the installation of embedded façade systems that dissipate heat.
- Passive design to enhance the geometric strategies to further optimize the shape factor to retain heat as well as to dissipate it.
- Heat sinks with a new shape inspired by the performance of animals, e.g. the toco-toucan or elephant, such as in (Zuazua-Ros et al., 2017a, 2017b), where the results have shown that the cooling capacity of this bio-inspired panel varies from 107 to 230 W/m^2 depending on the inlet temperature and fluid flow conditions, confirming the viability of the integration in buildings.
- Reduce (or even remove) cooling towers with embedded facade systems.
- Cooling load reduction as presented in (Yang and Li, 2008), where the effect of thermal mass on cooling load reduction in buildings is studied in detail using a simple building model, which allows to examine the hourly benefits in using thermal mass and night ventilation.

(2) System optimization:

- Minimization of equipment use. This means that architects, engineers and construction managers should make use of the minimum number of machines to achieve the performance objectives. Usually passive measures must be complemented with other active ones, e.g. by reducing consumption peaks, building services can be smaller and therefore take up less space (Martín-Gómez and Zuazua-Ros, 2012).
- Optimization of air ducts with solutions imported from insects' tracheoles.
- Reaching the target temperature with more efficient, yet not man-made tools already used by animals in extreme environmental conditions.
- Development of new heat recovery systems based on the retia mirabile of some aquatic species.

(3) New materials and/or products:

- Organic materials design to improve the removal of pollutants or volatile organic compounds in indoor spaces.
- Use of materials that diffract the light on façades and roofs.
- Products that reduce the reaction range of current detectors and sensors copied from insect behavior, as discussed in (Bermejo-Busto et al., 2016) where strategies such as the heat shield or stigmergy have been translated to obtain better control of the air cavity and a decentralized computational control of the equipment.

4.4. Results: case studies

Some hypotheses have already been developed or are under development by the research team. The up-to-date models and prototypes designed are briefly described in Table 3.

All the examples shown in Table 3 have been positive experiences resulting from the development of some of the subjects ascribed in Table 2. In fact, they have been published and some of them are currently at a second stage.

Each strategy corresponds to a different application field and scale. This circumstance is produced by the solution-based approach, where the brainstorming generated may lead the proposals to different areas. However, the final development always needs a previous background in the technology proposed.

It must be highlighted that when solutions are sought for low energy consumption in buildings, this does not mean the creation of a sophisticated control system for the systems managements, but rather having a holistic vision of the problem in order to propose alternative solutions (Zuazua-Ros et al., 2016a).

5. Discussion

This experience also confirms the theory that precise comprehension of biological systems can be ideal for detailed designs (Mak and Shu, 2008). Moreover, some potential and unexplored areas are shown for possible future research. The next steps of the research team will be the following:

- In-depth study of the relationship between buildings and social insects, especially in relation to ventilation issues.
- Development of new materials based on proteins capable of minimizing water evaporation.
- Air-inlet design in buildings based on the tracheoles of insects.
- Implementation of HVAC control systems with strategies that relate the building data networks with the stigmergy concept in animals (Fong et al., 2006).
- Redesign of thermic fluid pipes distribution systems from vessels control models.
- Implementation of stigmergy or emergent cooperation concept to use in control systems in autonomous HVAC systems (Salazar and Rodriguez-Aguilar, 2011). This application has been developed based mainly on the coordinated work done by social animals such as honeybees and ants. This strategy proceeding or system would be the 'neural network', taking 'stigmergy' as a second-level process and coordinated work as the action. In this case, neural networks are related to the data networks of buildings.

Regarding the experience of research with biomimicry, the following points have been especially relevant for the research group:

- The biologist group had a great knowledge of their area without awareness of the possibilities that could be valuable for buildings. This is the reason for the necessity to foster such collaboration among architects, engineers, biologists and experts from other fields of knowledge.
- Following the previous point, it is remarkable that the study of almost every animal analyzed offered either new implementation options for existing building energy

systems, or interesting hypotheses for the design of new solutions.

- It has been demonstrated that by considering one and the same animal strategy, different suitable solutions for buildings, or for the systems that integrate them, have been generated.

6. Conclusions

This paper has analyzed selected thermal strategies existing in animal species and has identified the immediate opportunity areas where strategies could be implemented. This study confirms the possibility of using biomimicry as basis for future research in building energy systems.

There are multiple research orientated ways to solve specific problems related to the construction and urban development, but there are little risky developments in cross-border investigations that meet researches and researchers from different profiles to solve technological and regulatory problems. This is why we sincerely believe that the academic, normative and methodological impact applied to the construction of this kind of research could be very high, with the empowerment of new and high-potential actors towards future technological leadership. In fact, the authors experience confirms the opportunity of the use of biomimicry not only in the 'traditional' development of architecture and engineering, but as a field of pending development in building services. Finally, the project observes the necessary cooperation of several disciplines, with multidisciplinary teams that promote transversal knowledge.

The study has validated the solution-based approach methodology proposed. On the one hand, the method permitted the creation of a relationship between the systems, processes and actions of animals, and the hypotheses for building. On the other, several potential research opportunities arose for different fields. Besides, insight case studies have been described in order to demonstrate the capacities of this technique.

The investigation confirms the opportunity of the use of biomimicry not only in the 'traditional' development of architecture and engineering, but as a field of pending development in building services. Finally, the project observes the necessary cooperation of several disciplines, with multidisciplinary teams that promote transversal knowledge.

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